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LOX/HYDROGEN COAXIAL INJECTOR ATOMIZATION TEST PROGRAM

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ABSTRACT

Quantitative information about the atomization of injector sprays is required to improve the accuracy of computational models that predict the performance and stability margin of liquid propellant rocket engines. To obtain this information, a facility for the study of spray atomization is being established at the NASA Lewis Research Center to determine the drop size and velocity distributions occurring in vaporizing liquid sprays at supercritical pressures. Hardware configuration and test conditions are selected to make the cold flow simulant testing correspond as closely as possible to conditions in liquid oxygen (LOX)/gaseous hydrogen rocket engines. Drop size correlations from the literature, developed for liquid/gas coaxial injector geometries, are used to make drop size predictions for LOX/hydrogen coaxial injectors. The mean drop size predictions for a single element coaxial injector range from .1 to 2000 μm, emphasizing the need for additional studies of the atomization process in LOX/hydrogen engines. Selection of cold flow simulants, measurement techniques, and hardware for LOX/hydrogen atomization simulations are discussed.

INTRODUCTION

Obtaining information about the atomization of injector sprays has been identified by the JANNAF Liquid Rocket Combustion Instability Panel (Ref. 1) and the JANNAF Performance of Solid and Liquid Rockets Panel (Ref. 2) as critical to improving the accuracy of computational models that predict the performance and stability margin of liquid propellant rocket engines. The drop size and velocity distributions produced at the completion of atomization are the initial conditions for vaporization, mixing, and combustion stability analyses in liquid propellant combustors. Therefore, atomization information is crucial to the analyst's ability to make hardware performance and stability predictions. If accurate predictions could be made, the expensive testing performed in engine development programs could be reduced, combustion instabilities could be avoided, and the efficiency of new engines could be optimized. Unfortunately, the physics of atomization are not well understood, and empirical correlations must be relied on to estimate drop size distributions in spray combustion systems.

Computer codes, such as the Coaxial Injection Combustion Model (CICM) (Ref. 3), the High-Frequency Injection Coupled Combustion Instability Program (HICCIP) (Ref. 4), and the Rocket Combustor Interactive Design Methodology (ROCCID) (Ref. 5), calculate a spray size distribution to estimate performance and stability margin. Some codes use drop size correlations derived from cold flow test results. Other codes contain equations with adjustable parameters that have been calibrated by forcing the overall performance predictions to agree with actual performance measurements. No rocket combustor hot fire data exist that can verify the drop size and velocity predictions of these codes. Drop size and velocity measurements, as well as local gas velocity measurements, collected in operating combustors using non-intrusive techniques, are required to validate the atomization models and improve modeling capabilities (Ref. 6,7). Drop velocity measurements are also required to determine droplet vaporization rates. Since the combustion process in liquid propellant rocket engines is primarily vaporization limited (Ref. 8), drop size and velocity information is critical to predicting performance and combustion stability. Size and velocity measurements of vaporizing droplets at supercritical conditions are especially needed to validate supercritical vaporization models.

In response to the JANNAF Panel recommendations, and the lack of data needed to validate and improve existing atomization models, a spray atomization testing facility is being established at the NASA Lewis Research Center (LeRC). This facility will be used to obtain simultaneous drop size, velocity, and local gas velocity measurements in sprays that simulate the fluid properties occurring in LOX/hydrogen rocket engines. Based on previous studies, the diagnostic techniques, hardware, and non-reacting simulants that can accomplish this task are selected. An evaluation of current drop size predictive capability is conducted, by using existing atomization correlations to make drop size predictions for the test hardware.

PROGRAM DESCRIPTION

A test program is being conducted at the NASA Lewis Research Center to obtain hot fire atomization data in liquid oxygen (LOX)/gaseous hydrogen coaxial injector sprays. Before hot fire testing is attempted, non-reacting, supercritical pressure, vaporizing sprays will be studied to determine the feasibility of making measurements in such sprays. High speed photography and particle sizing interferometry will be used to obtain information about the spray structure, droplet size distributions, droplet velocity distributions, and local gas velocity distributions. An additional series of tests will be conducted, in both cold flow and hot fire sprays, using a high pressure cross flow of gas. This radial gas flow will attempt to simulate the effects of high frequency combustion instability pressure waves on the atomization process. Finally, the relationship between the cold flow and hot fire data will be established.

DIAGNOSTIC TECHNIQUES

Non-intrusive laser-based diagnostics, often employed to obtain quantitative drop size information, require optical access to the spray. The high pressure, high temperature environment of rocket combustors makes providing and maintaining optical access difficult. Rocket test facilities are expensive to operate, and are not generally built to allow application of laser diagnostics to the engines. Due to the difficulty of making drop size measurements in hot firing rocket engines, very little rocket combustor drop size data exist. Ingebo (Ref. 9) photographed droplets in a 0.7 MPa (100 psia) LOX/ethanol engine, and obtained drop sizes and velocities from the photographs. George (Ref. 10) used holography to measure drop sizes in a 1.1 MPa (150 psig) NTO/MMH engine. Conducting photographic studies was extremely time-consuming, since each droplet had to be measured and counted manually. A relatively small number of droplets was counted in both these experiments (less than 2000 at each condition), contributing to uncertainty in the droplet size-number distributions.

Hot wax freezing and laser-based line-of-sight techniques, have commonly been used to obtain atomization information about coaxial injector sprays (Ref. 11-18). Neither of these commonly used techniques obtain drop velocities. Advances in image processing have made photographic techniques easier to use, but photographic techniques only measure the instantaneous concentration of drops. Instantaneous drop concentration measurements have been shown to be less useful than droplet flux measurements for validating computer codes (Ref. 6,7). Single particle counting techniques are needed to obtain droplet flux information, since these techniques can measure drop size and velocity simultaneously. Particle sizing interferometry (PSI), a single particle counting technique, has been selected for the LOX/hydrogen atomization testing program. PSI can be used to obtain drop sizes, velocities, and local gas velocities. It has been applied successfully to reacting spray flames (Ref. 19,20). PSI must be applied carefully, since it can only measure spherical drops, and is sensitive to alignment. Detailed information about various laser-based drop sizing techniques, including single particle counters, is provided by Hirleman (Ref. 21). Photography will be used to determine the overall spray structure, and to find regions of the spray where PSI could reasonably be applied.

HARDWARE

A single-element, shear coaxial injector has been fabricated for use in hot fire and cold flow atomization testing. The injector consists of four parts: a LOX inlet, LOX post, gas manifold, and face plate (Fig. 1). By changing out the LOX post and face plate, several injector geometries can be evaluated with the same gas manifold, decreasing fabrication cost and down time between test runs. The LOX post has four fins to center it within the gas manifold. Five injector geometries, with varying liquid injection areas and gas injection areas have been selected. These injector geometries are listed in Table I. Different injector geometries will be tested to examine the effect of varying the injector geometry on the atomization process. The injector element, designed for a nominal 330 N (75 lbf) thrust at 5.5 Mpa (800 psia) chamber pressure, is smaller than SSME main chamber injector elements, but approximately the same size as RL-10 injector elements. A small injector size was selected to reduce the spray number density, and permit application of optical drop sizing diagnostics.

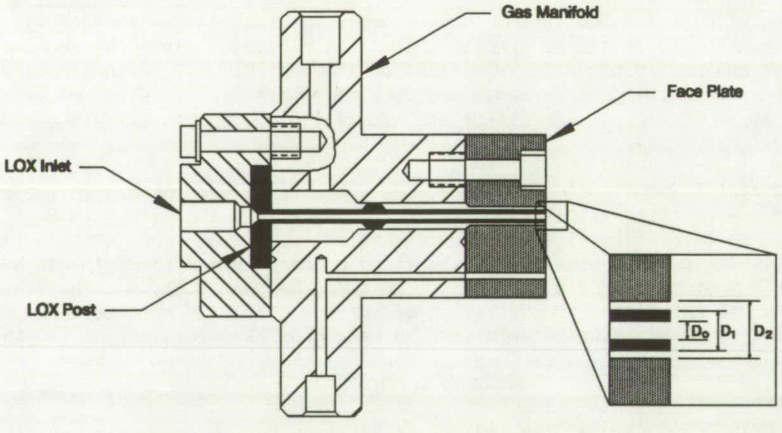

Figure 1. Shear Coaxial Injector Design

Table I. LeRC Modular Coaxial Injector Configurations

	No. 1	No. 2	No. 3	No. 4	No. 5
D_2, cm (in)	.594 (.234)	.594 (.234)	.516 (.203)	.594 (.234)	.437 (.172)
D_1, cm (in)	.396 (.156)	.318 (.125)	.318 (.125)	.396 (.156)	.318 (.125)
D_o, cm (in)	.132 (.052)	.132 (.052)	.132 (.052)	.198 (.078)	.132 (.052)

A chamber has been designed for the cold flow and hot fire atomization tests (Fig. 2). The chamber has a maximum working pressure of 6.9 MPa (1000 psia), and diameter of 5 cm (2 in.). Recirculation problems, such as Ferrenberg (Ref. 22) encountered when attempting to measure drop sizes in pressurized chambers, are not anticipated, since cryogenic test liquids will be used. Small droplets are expected to evaporate quickly, instead of continually being recirculated back to the injector face. A cylindrical chamber was chosen over square chamber designs, in order to simulate actual rocket engine recirculation patterns more closely. The chamber will be composed of several segments, which could be rearranged to move the window axially, or alter the chamber length. A similar segmented chamber design was used by Burrows (Ref. 23) in a 2.4 MPa (350 psia) LOX/hydrogen rocket engine. Two different windowed chamber segments will be used. One windowed segment will be used for the cryogenic temperature cold flow testing, and another for the extremely high temperature, hot fire testing. A small nitrogen purge has been included upstream of each window. The nitrogen purges will provide cooling for the hot fire testing chamber, and will help keep the windows clear of spray. Another gas port will be located at the side of the injector face. The face port will be used only for the cross flow atomization tests.

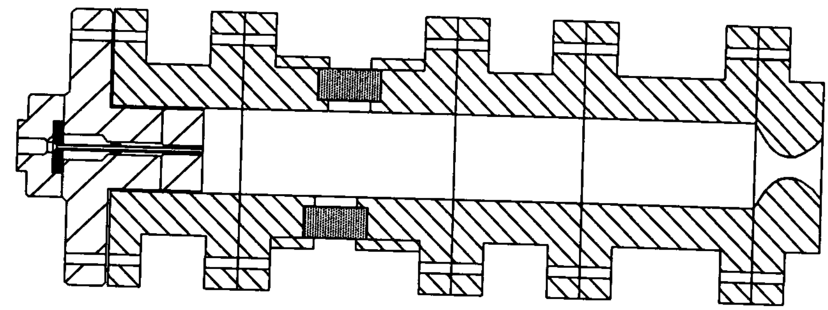

Figure 2. High Pressure Chamber Design

Quartz, sapphire, fused silica, and plexiglas windows have been used in pressurized chambers where optical access was required. Quartz and sapphire have optical properties that are a function of direction (birefringence), making the application of off-axis particle sizing interferometry complicated. Fused silica is homogeneous and has high transmissibility. Plexiglas was discarded as a possible window material due to its low melting temperature. Although the strength and temperature resistance of sapphire are superior to those of fused silica, the birefringent properties of sapphire are difficult to overcome for this application, so fused silica windows were selected for the atomization testing.

The feasibility of measuring drop sizes with the proposed window configuration and material was examined using a particle sizing interferometer (PSI) (Ref. 24) and a Berglund-Liu monodisperse droplet generator. The droplet generator was set up to produce a monodisperse stream of 110 μm water droplets. Two 1" thick fused silica windows were placed in the PSI transmitter and detector paths. For these moderately thick pressure chamber windows, due to refraction of the beams by the windows, the probe volume was formed after the minimum diameter of the focussed beams, in the diverging sections of the beams. The interference fringes in the probe volume were no longer parallel, making the measured drop size vary by as much as 30% across the probe volume length (Fig. 3). The optical setup must be altered to allow independent movement of the focussed beam spots (minimum diameters) and the focusing lens (Ref. 25), so that the beams have a minimum diameter at the point of intersection.

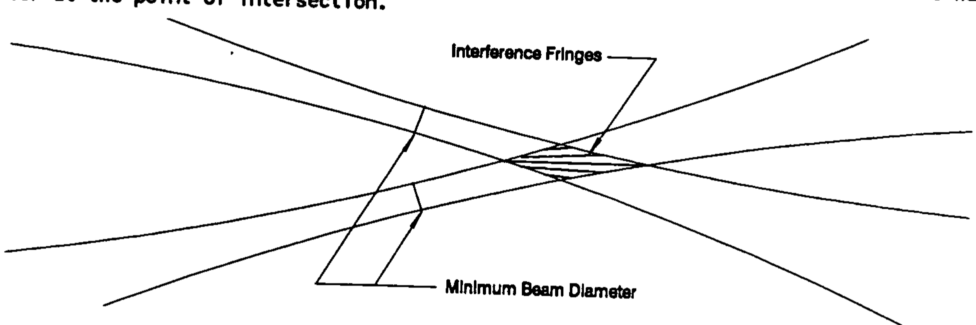

Figure 3. Effect of Refraction on Interference Fringes

LITERATURE REVIEW

Many atomization correlations have been derived from experiments using cold flowing simulants with properties that are very different from the reactants under consideration. Empirical drop size correction factors relating the properties of the simulant to the actual propellant properties are occasionally employed, such as the property correlations attributed to Ingebo (Ref. 13) and Wolfe and Anderson (Ref. 6). A literature survey was conducted to identify atomization correlations applicable to coaxial injectors. Any

correlation developed for injectors employing liquid jet breakup by high velocity, co-flowing gas streams was considered applicable. These correlations are presented in Table II. Detailed atomization literature reviews are given by Ferrenberg (Ref. 22) and Lefebvre (Ref. 26). Several researchers based their correlations on experimental data for which injection parameters, such as the liquid properties, were widely varied. Most of the data for these correlations were collected using either laser diffraction techniques or hot wax freezing techniques.

Table II. Atomization Correlations Applicable to Coaxial Injectors

Reference	Correlation
Nukiyama, Tanasawa (Ref. 27)	$\overline{D}_{32} = \frac{585}{V_r}\sqrt{\frac{\sigma}{\rho_L}} + 597\left(\frac{\mu_L}{\sqrt{\sigma\rho_L}}\right)^{.45}\left(1000\frac{Q_L}{Q_g}\right)^{1.5}$
Weiss, Worsham (Ref. 11)	$D_{V0.5} = .61\left(1 + 1000\frac{\rho_g}{\rho_L}\right)\left(\frac{V_r\mu_L}{\sigma}\right)^{2/3}\left(\frac{\sigma}{\rho_g V_r^2}\right)\left(\frac{W_T\rho_L\sigma\mu_g}{\mu_L^4}\right)^{1/12}$
Mayer (Ref. 28)	$D_{V0.5} = 9\pi\sqrt[3]{16}\,B\left(\frac{\mu_L\sigma^{1/2}}{\rho_g V_g^2\rho_L^{1/2}}\right)^{2/3}$
Kim, Marshall (Ref. 12)	$D_{V0.5} = \frac{249\sigma^{.41}\mu_L^{.32}}{(V_r^2\rho_g)^{.57}A_g^{.36}\rho_L^{.16}} + \frac{1260}{V_r^{.54}}\left(\frac{\mu_L^2}{\sigma\rho_L}\right)^{.17}\left(\frac{W_L}{W_g}\right)$
Rizkalla, Lefebrve (Ref. 14)	$\overline{D}_{32} = \frac{521\sigma^{.5}\rho_L^{.75}}{V_g}\left(1 + \frac{W_L}{W_g}\right) + .037\mu_L^{.85}(\sigma\rho_L)^{1.2}\left(1 + \frac{W_L}{W_g}\right)^2$
Lorenzetto, Lefebvre (Ref. 15)	$\overline{D}_{32} = .95\left(\frac{\sigma^{.33}W_L^{.33}}{V_r\rho_L^{.37}\rho_g^{.3}}\right)\left(1 + \frac{W_L}{W_g}\right)^{1.70} + .13\mu_L\left(\frac{D_o}{\sigma\rho_L}\right)^{.5}\left(1 + \frac{W_L}{W_g}\right)^{1.70}$
Jasuja (Ref. 16)	$\overline{D}_{32} = .022\left(\frac{\sigma_L}{\rho_g V_g^2}\right)^{.45}\left(1 + \frac{W_L}{W_g}\right)^{.5} + 14.3\times10^{-4}\left(\frac{\mu_L^2}{\sigma\rho_L}\right)^{.4}\left(1 + \frac{W_L}{W_g}\right)^{.8}$
Ingebo (Ref. 17)	$\frac{D_o}{\overline{D}_{32}} = 1.2\left(\frac{\rho_g^2 D_o^2 V_r^3}{\sigma\mu_L}\right)^{.4}\left(\frac{g\lambda}{V_m^2}\right)^{.15}$
Hautman (Ref. 18)	$\overline{D}_{32} = 2.55\times10^5\left(1 + \frac{W_g V_g}{W_L V_L}\right)^{-2}\left(\frac{\sigma^{.44}\rho_L^{.29}}{\rho_g^{.35}\Delta p_L^{.59}AR^{.34}}\right)$

According to the atomization theory proposed by Mayer (Ref. 28), the droplet sizes resulting from the breakup of a liquid jet by a high velocity gas stream are a function of the liquid surface tension, viscosity, and density, as well as orifice diameter and atomizing gas velocity. The relative influence of each of these parameters on the drop size distribution is not known. Numerous correlations relating injection parameters to drop sizes produced at the completion of atomization have been proposed. These correlations, often developed using a variety of non-reacting fluids, are applied to reacting sprays. Data are usually taken at ambient pressure and temperature, instead of the high temperature and high pressure environment of operating combustors. The gas and liquid injection velocities are used as input for these correlations: the actual velocity field downstream of the injection plane is ignored.

To assess the agreement among the correlations in Table II, these correlations were used to make drop size predictions for the LeRC modular coaxial injector (Fig. 1). The hot fire injection parameters for three of the LeRC modular coaxial injector configurations were calculated (Table III). These three injector configurations were selected for which the relative gas/liquid velocity varied over a wide range. These hot fire parameters were substituted into each atomization correlation, and a mean drop size was predicted (Table IV).

Some correlations predict the mass median diameter ($D_{V0.5}$), while others predict the Sauter mean diameter ($\overline{D}_{32}$), contributing to variation in the drop size predictions. This variation cannot be calculated exactly, since the atomization correlations provide no information about the shape of the drop size distributions. Simmons (Ref. 29) compared the Sauter mean diameter and the mass median diameter of 200 drop

size distributions obtained from tests of various fuel nozzles. Simmons found that the mass median diameter of the distributions was 1.2 times the Sauter mean diameter to within 5%. The drop sizes predicted by the three mass median diameter correlations (Weiss and Worsham, Mayer, Kim and Marshall) were reduced by a factor of 1.2. Only the adjusted Sauter mean diameter predictions for the correlations in Table II are reported in Table IV.

Table III. LOX/Hydrogen Injection Parameters

Injection Parameters	LeRC Modular Injector Configuration No. 1	No. 2	No. 3
D_o, cm (in)	.132 (.052)	.132 (.052)	.132 (.052)
A_g, cm^2 (in^2)	.198 (.0307)	.130 (.0201)	.0710 (.0110)
W_L, kg/s (lb/s)	.0838 (.185)	.0873 (.192)	.0898 (.198)
W_g, kg/s (lb/s)	.0210 (.0462)	.0179 (.0395)	.0159 (.0350)
ρ_L, kg/m^3 (lb/ft^3)	1080 (67.2)	1080 (67.2)	1080 (67.2)
ρ_g, kg/m^3 (lb/ft^3)	4.47 (.279)	4.47 (.279)	4.47 (.279)
ΔP_L, MPa (psi)	1.75 (254)	1.90 (275)	2.01 (291)
V_L, m/s (ft/s)	57.0 (187)	59.4 (195)	61.1 (200)
V_g, m/s (ft/s)	237 (777)	308 (1010)	502 (1650)
V_r, m/s (ft/s)	180 (591)	249 (817)	441 (1450)
σ, N/m (lb/ft)	9.72 E-3 (6.66 E-4)	9.72 E-3 (6.66 E-4)	9.72 E-3 (6.66 E-4)
μ_L, kg/m·s (lb/ft·s)	1.46 E-4 (9.84 E-5)	1.46 E-4 (9.84 E-5)	1.46 E-4 (9.84 E-5)
μ_g, kg/m·s (lb/ft·s)	8.99 E-6 (6.04 E-6)	8.99 E-6 (6.04 E-6)	8.99 E-6 (6.04 E-6)

Table IV. Drop Size Predictions for LOX/Hydrogen Testing

	Sauter Mean Diameter, µm No. 1	No. 2	No. 3
Nukiyama, Tanasawa (Ref. 27)	1300	1700	2100
Weiss, Worsham (Ref. 11)	2.5	1.6	0.8
Mayer (Ref. 28)	.26	.18	.09
Kim, Marshall (Ref. 12)	24	24	21
Rizkalla, Lefebvre (Ref. 14)	39	37	28
Lorenzetto, Lefebvre (Ref. 15)	380	370	260
Jasuja (Ref. 16)	24	21	16
Ingebo (Ref. 17)	47	32	16
Hautman (Ref. 18)	8.2	7.6	5.2

The drop size predictions for the LeRC coaxial hardware vary from 0.1 to 2000 μm. No correlation predicts mean drop sizes within 10% of any other correlation for all three hardware configurations that were examined. This wide range of predictions emphasizes the current lack of understanding of the atomization process, and the need for data that can be used for atomization model validation. Some of these correlations were developed using a variety of non-reacting fluids, flow rates, and geometries, with the goal of making the correlation applicable to a wide range of hot fire conditions. However, the injection conditions in LOX/hydrogen engines are quite different from the injection conditions previously studied, especially the high relative gas/liquid velocity, high chamber density, and low liquid surface tension. Therefore, additional studies for validation of LOX/hydrogen atomization models should better simulate the conditions encountered in LOX/hydrogen engines.

SELECTION OF NON-REACTING SIMULANTS

Since the conditions in LOX/hydrogen rocket engines are very different from any encompassed in previously conducted atomization studies, atomization testing is required that simulates LOX/hydrogen engines more closely. A non-reacting liquid simulant is needed that is safer to use than LOX, can be vaporized, and has a relatively low critical pressure. Liquid nitrogen satisfies these requirements. The properties of LOX and liquid nitrogen, along with the properties of other liquids that have been previously used as LOX simulants, are listed in Table V. To assess the ability of these liquids to simulate LOX atomization, the liquid properties were substituted into the atomization correlations in Table II, and a mean drop size was predicted for the second LeRC coaxial injector configuration. The drop size predictions for the various liquids are presented in Table VI. By comparing the drop size predictions for all the liquids to the LOX drop size predictions, it can be seen that liquid nitrogen simulates LOX more closely than any of the other liquids.

Table V. Liquid Properties of Commonly Used LOX Simulants

	Temperature K(°R)	Pressure MPa(psia)	Surface Tension N/m(lb/ft)	Density kg/m^3(lb/ft^3)	Viscosity kg/m·s(lb/ft·s)
Liquid Oxygen	106 (190)	5.51 (800)	.0097 (6.7 E-4)	1080 (67.2)	1.5 E-4 (9.8 E-5)
Liquid Nitrogen	83.3 (150)	4.14 (600)	.0074 (5.1 E-4)	788 (49.2)	1.4 E-4 (9.7 E-5)
Freon 113	298 (537)	.101 (14.7)	.019 (1.3 E-3)	1565 (97.7)	6.8 E-4 (4.6 E-4)
Jet A (Ref. 18)	298 (537)	.101 (14.7)	.026 (1.8 E-3)	806 (50.3)	1.5 E-3 (1.0 E-3)
Shellwax 270 (Ref. 13)	---	---	.017 (1.2 E-3)	764 (47.7)	1.8 E-3 (2.7 E-3)
Water	298 (537)	.101 (14.7)	.072 (4.9 E-3)	997 (62.2)	8.9 E-4 (6.0 E-4)

Table VI. Predicted Mean Drop Sizes (μm) for Different Liquids

	Liquid Oxygen	Liquid Nitrogen	Freon 113	Jet A	Shellwax 270	Water
Nukiyama, Tanasawa (Ref. 27)	1700	1900	2700	4100	7100	2500
Weiss, Worsham (Ref. 11)	1.9	2.2	3.3	7.9	9.6	8.6
Mayer (Ref. 28)	.22	.22	.67	1.6	2.7	1.5
Kim, Marshall (Ref. 12)	29	32	42	58	86	42
Rizkalla, Lefebvre (Ref. 14)	37	25	110	110	130	280
Lorenzetto, Lefebvre (Ref. 15)	370	380	400	590	600	730
Jasuja (Ref. 16)	21	20	31	40	51	51
Ingebo (Ref. 17)	32	28	76	120	150	150
Hautman (Ref. 18)	7.6	6.2	11	11	9.0	18

The liquid properties were also substituted into two property correlations (6,13) that have been used to "correct" the predicted drop size in hot wax experiments. The correction factors relate the properties of different liquids to the properties of LOX. Both of these correlations predict that liquid nitrogen properties are so similar to LOX properties, that almost no drop size correction would be required. The predicted correction factors are included in Table VII.

Table VII. Drop Size Correction Factors for Different Liquids

	Liquid Oxygen	Liquid Nitrogen	Freon 113	Jet A	Shellwax 270	Water
Wolfe, Anderson (Ref. 6)	1.0	.98	.52	.24	.21	.19
Ingebo (Ref. 13)	1.0	.99	.63	.41	.35	.38

Two criteria are used for the gaseous hydrogen simulant selection. A gaseous simulant is needed that is relatively non-hazardous, and could be used to match the high injection velocities of hydrogen. Gaseous helium was selected, since it is inert and has a high sonic velocity. The sonic velocity of higher molecular weight gases, such as nitrogen, is lower than the hydrogen injection velocity predicted for the LeRC modular coaxial injector. The use of these heavier gases would prevent gas velocity matching between the cold flow and hot fire cases.

CONCLUDING REMARKS

There is wide disagreement among drop size correlations currently available for coaxial types of injectors. Additional studies of the atomization of supercritical pressure, vaporizing sprays are required to increase our understanding of the liquid breakup process, and to obtain data useful for validation of computer models that predict performance and stability margin of LOX/hydrogen engines. To accomplish this task, a facility is being established at the NASA Lewis Research Center to examine the atomization of high pressure cryogenic sprays. Based on the results of numerous atomization studies, liquid nitrogen and gaseous helium are shown to closely simulate the properties of liquid oxygen and gaseous hydrogen. It is anticipated that cold flow and reacting spray studies, using liquid nitrogen/gaseous helium and liquid oxygen/gaseous hydrogen, respectively, will result in similar spray distributions. To test this hypothesis, particle sizing interferometry and high speed photography will be applied to non-reacting sprays to obtain information about spray structure, droplet size and velocity distributions, and local gas velocity. Future plans include LOX/hydrogen testing employing the same diagnostic techniques and hardware as the cold flow testing. The data obtained from this program will be useful for validating existing atomization models, assessing the accuracy of previously developed drop-size correlations, and establishing benchmark data for computational codes that attempt to model liquid breakup from first principles.

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NOMENCLATURE

A	Injection Area, cm^2 (in^2)
AR	Tangential-Slot-to-Inner-Tube Area Ratio (0.74), Ref. 18
B	Jet Stripping Parameter (0.3), Ref. 28
D_o	Liquid Orifice Diameter, cm (in)
D_1	LOX Post Diameter, cm (in)
D_2	Gas Annulus Diameter, cm (in)
$\bar{D}_{32}$	Sauter Mean Diameter, μm
$D_{V0.5}$	Volume Median Diameter, μm
g	Acceleration due to Gravity, m/s^2 (ft/s^2)
LOX	Liquid Oxygen
NTO/MMH	Nitrogen Tetroxide/Monomethyl Hydrazine
PSI	Particle Sizing Interferometry
Q	Volumetric Flow Rate, m^3/s (ft^3/s)
SSME	Space Shuttle Main Engine
V	Velocity, m/s (ft/s)

W	Mass Flow Rate, kg/s (lb/s)
ΔP	Pressure Drop, MPa (psi)
λ	Molecular Mean Free Path, m (ft)
μ	Viscosity, kg/m·s (lb/ft·s)
ρ	Density, kg/m^3 (lb/ft^3)
σ	Surface Tension, N/m (lb/ft)

Subscripts

g	Gas
L	Liquid
m	Molecular
r	Relative
T	Total

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